Searching for Dark Matter with MiniBooNE

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On behalf of the MiniBooNE collaboration

FNAL Physics Advisory Committee Meeting
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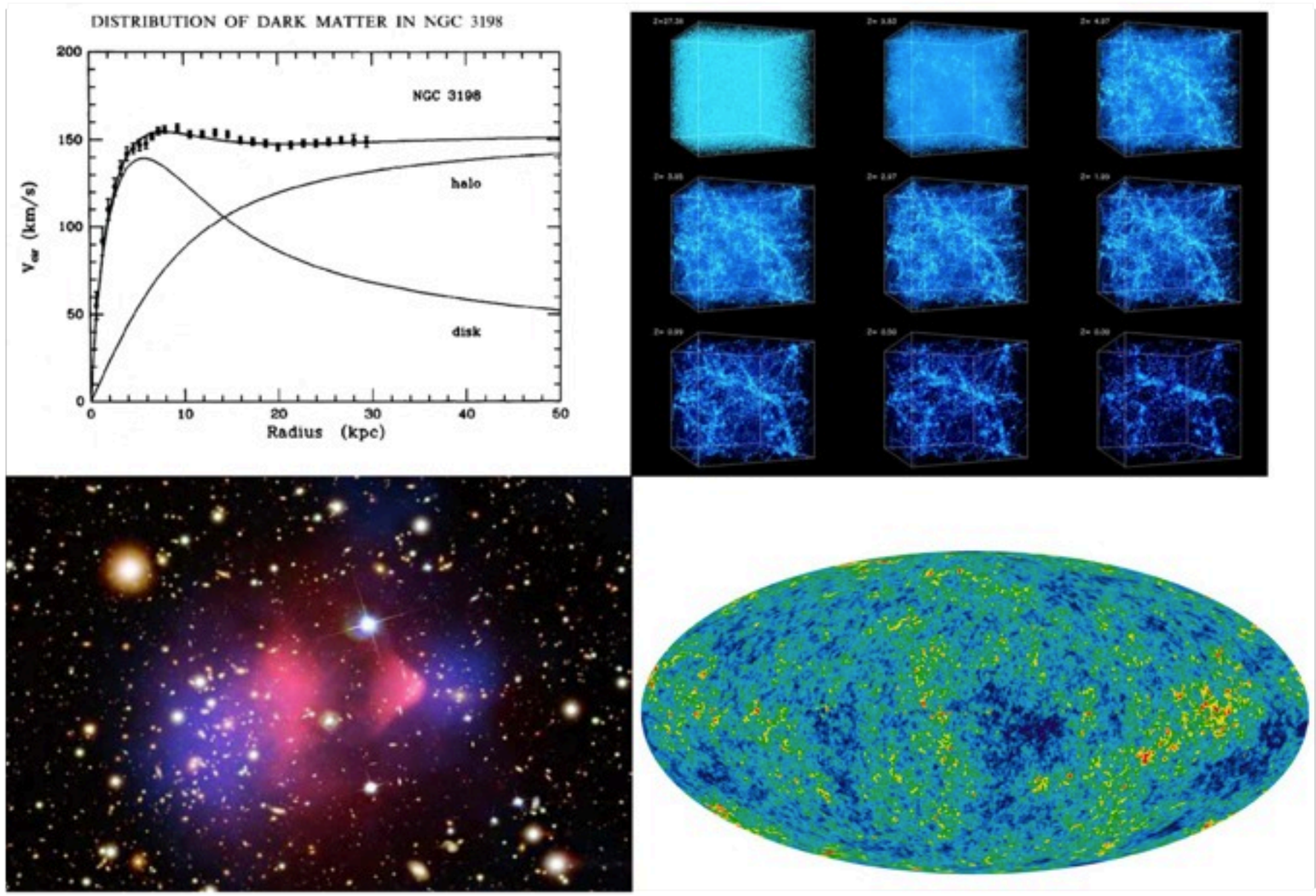
Outline

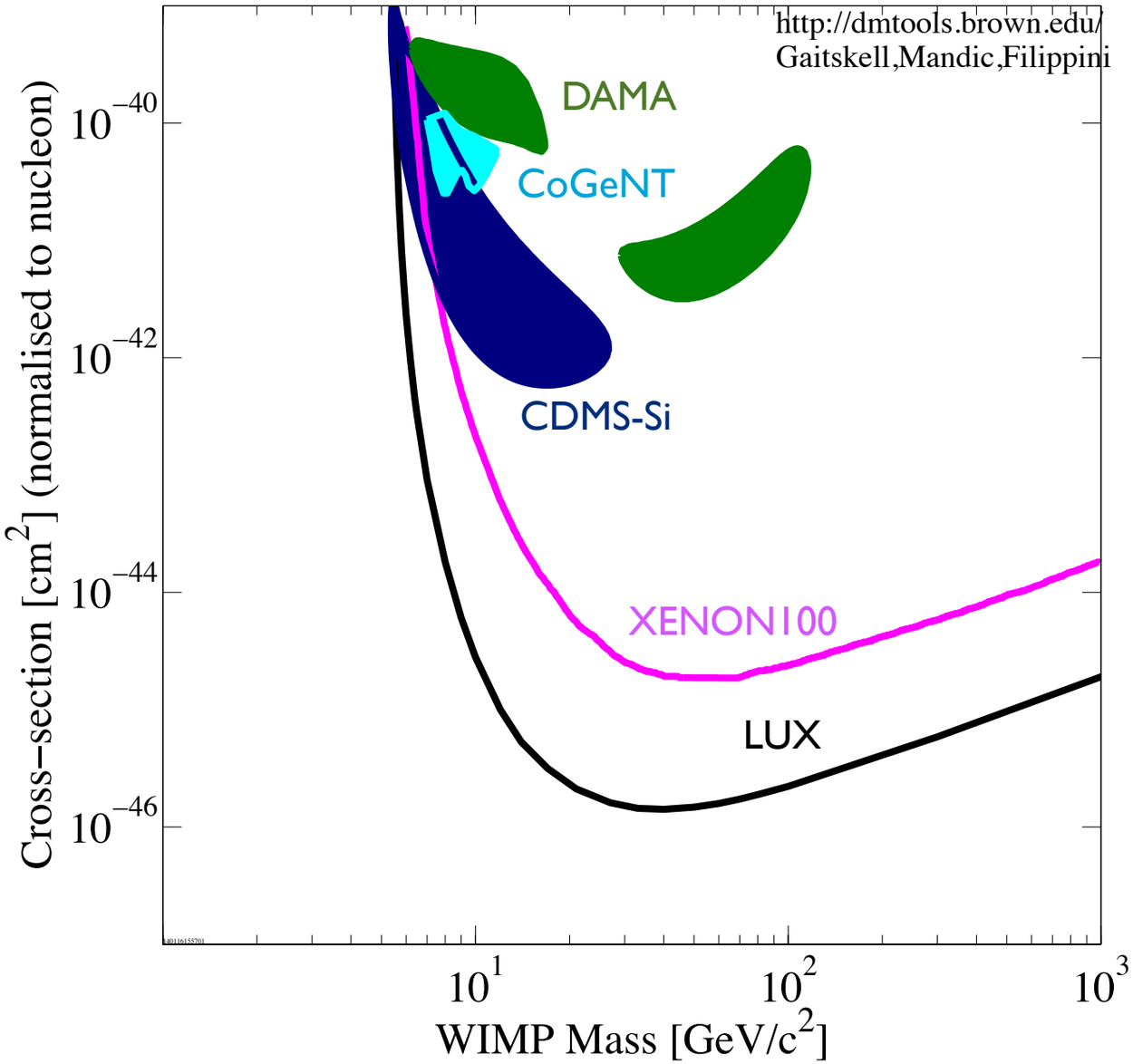
- Motivation and basic experimental principle
- Benchmark model and signal calculation
- Enhanced dark matter sensitivity in beam-dump mode
- MiniBooNE dark matter search methods and sensitivities
- Run issues & logistics
- Summary and request for further running

Dark Matter



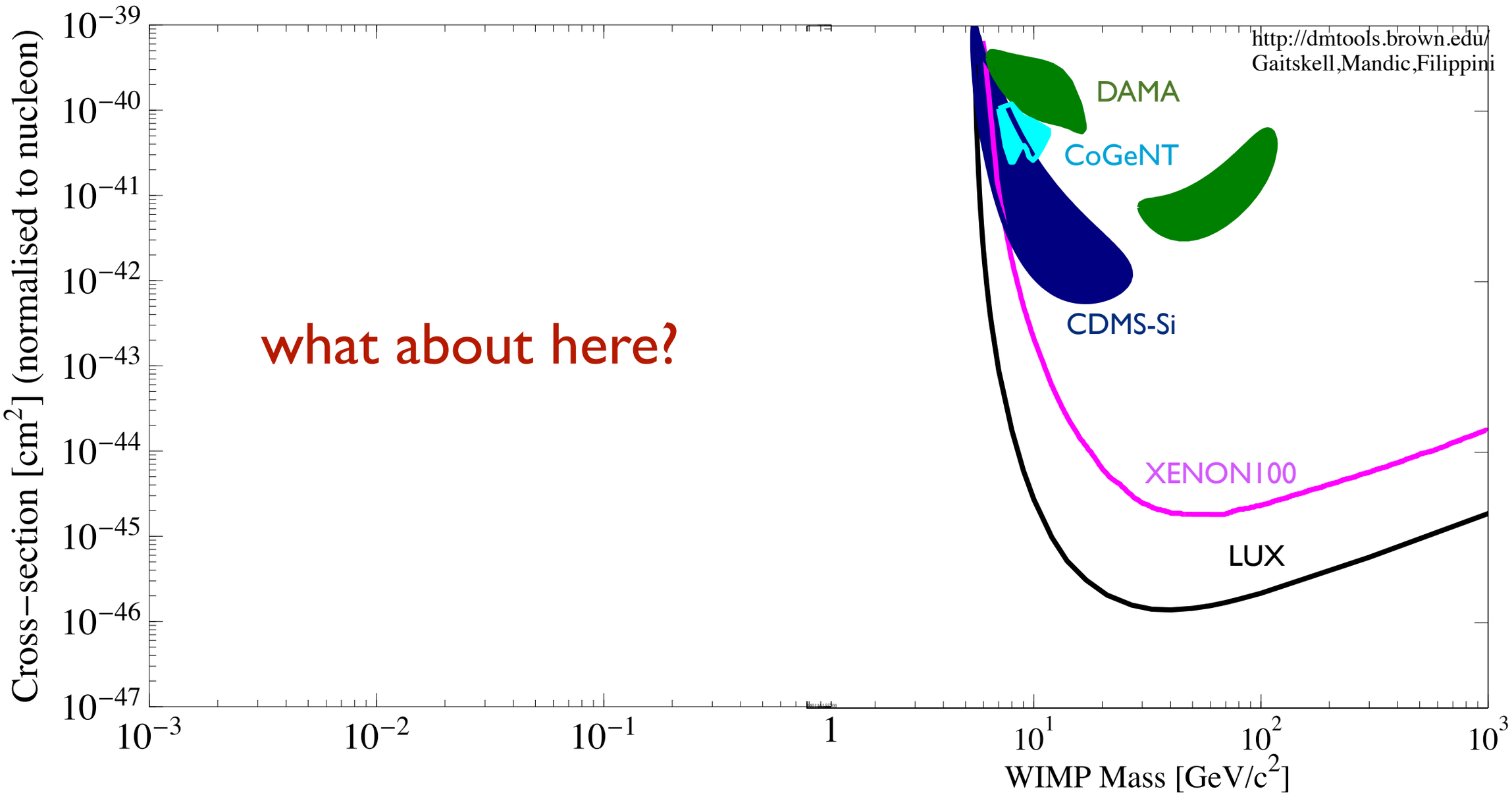
- One of the few empirical hints of new physics
- Detecting non-gravitational interactions of DM is a top-priority

Direct Detection



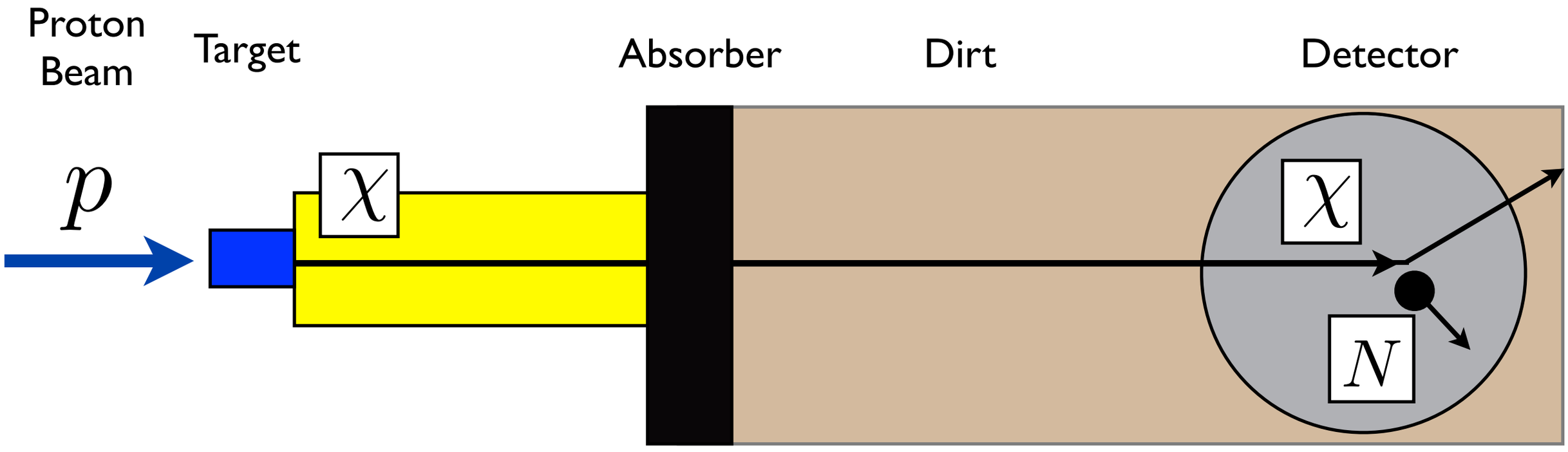
- Enormous progress over past 2 decades
- Probe DM masses above ~ 5 GeV

Direct Detection



- Nuclear recoil too weak - $v_{\mathrm{DM}} \sim 10^{-3}$
- Can we find a relativistic source of Dark Matter?

Relativistic Dark Matter Beam!



[BB, Pospelov Ritz, '09]
[deNiverville, Pospelov, Ritz, '11]
[deNiverville,McKeen,Ritz,'12]

High intensity proton beams are the foundation of the FNAL experimental program

The search for dark matter provides a new strong physics motivation for this program!

Why Light Dark Matter? Why not!

Dark Matter provides one of the few *empirical* hints for new dynamics

But, absolutely no empirical suggestion for the mass of the DM

A great deal of attention has been given to the WIMP

"WIMP miracle" - particle with weak scale mass, weak interactions yields the observed dark matter relic abundance

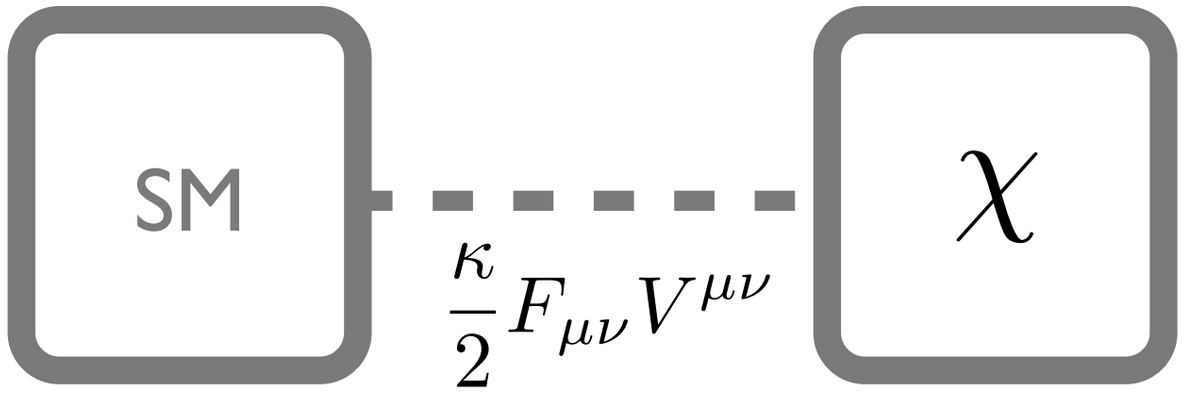
In tandem with the hierarchy problem, WIMP is a compelling picture for DM!

But so far, no new physics at LHC - perhaps DM is not at the weak scale

Dark sector may be complicated - multi-component, several mass scales

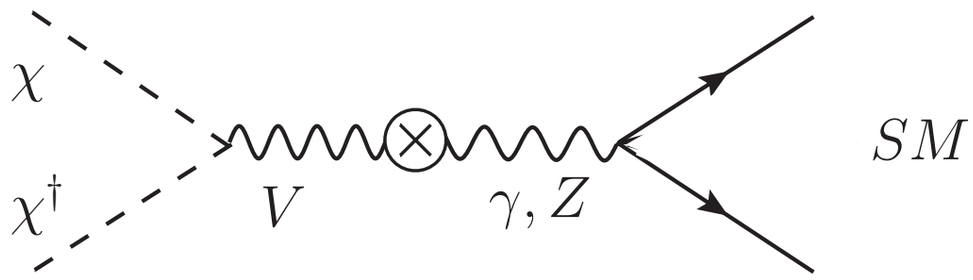
We must search everywhere we can for Dark Matter,
both high mass and low mass!

Benchmark vector portal model of light dark matter



[Holdom]
[Pospelov, Ritz, Voloshin,
[Hooper, Zurek]
[Arkani-Hamed, et al]
... and many others

- Dark photon mediates interaction between DM and SM
- 4 new parameters: $m_\chi, m_V, \kappa, \alpha'$
- Can obtain correct relic abundance

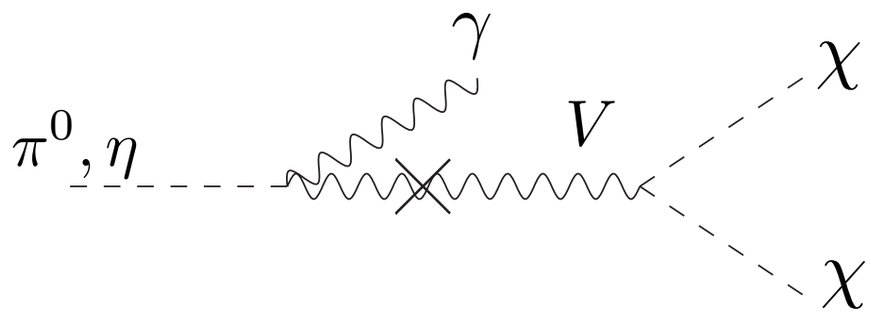


- Dark photon can address g-2 anomaly [Fayet, Pospelov]

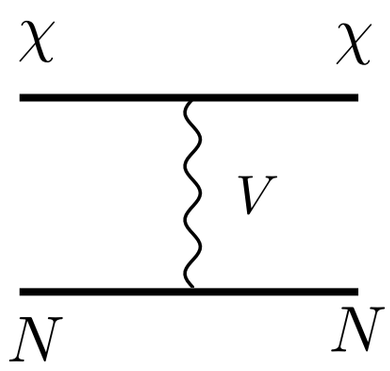
Simple, viable model - this will be our benchmark
Of course, other scenarios are possible!

Production of the Dark Matter beam

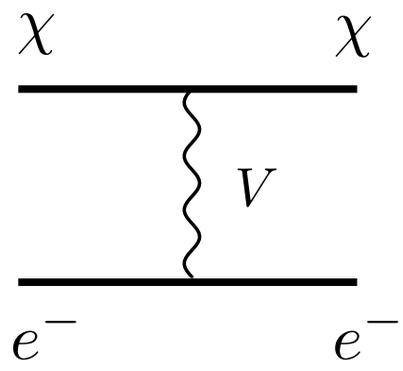
Decays of mesons:



Dark Matter detection via scattering



$\chi -$ nucleon elastic

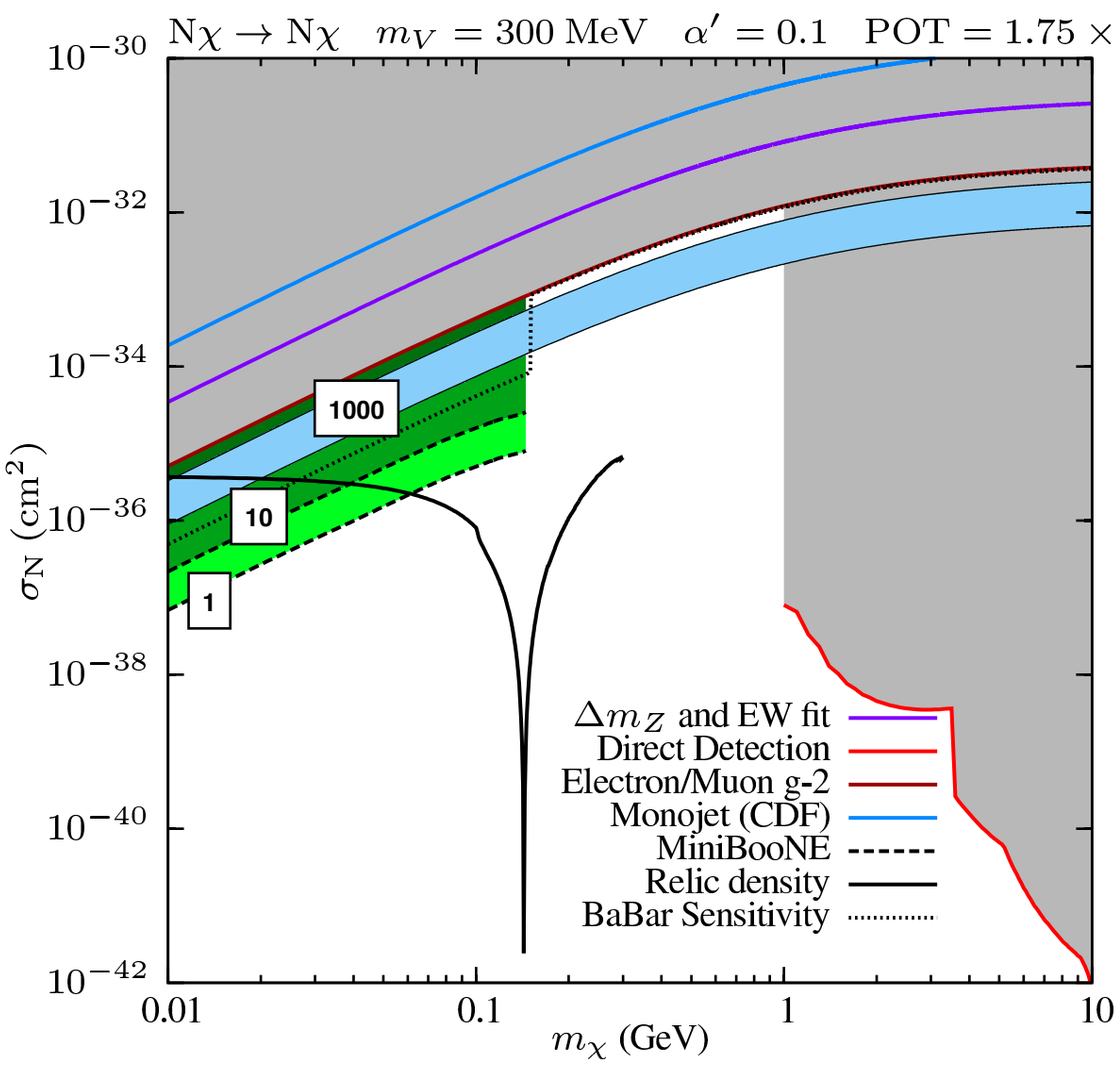


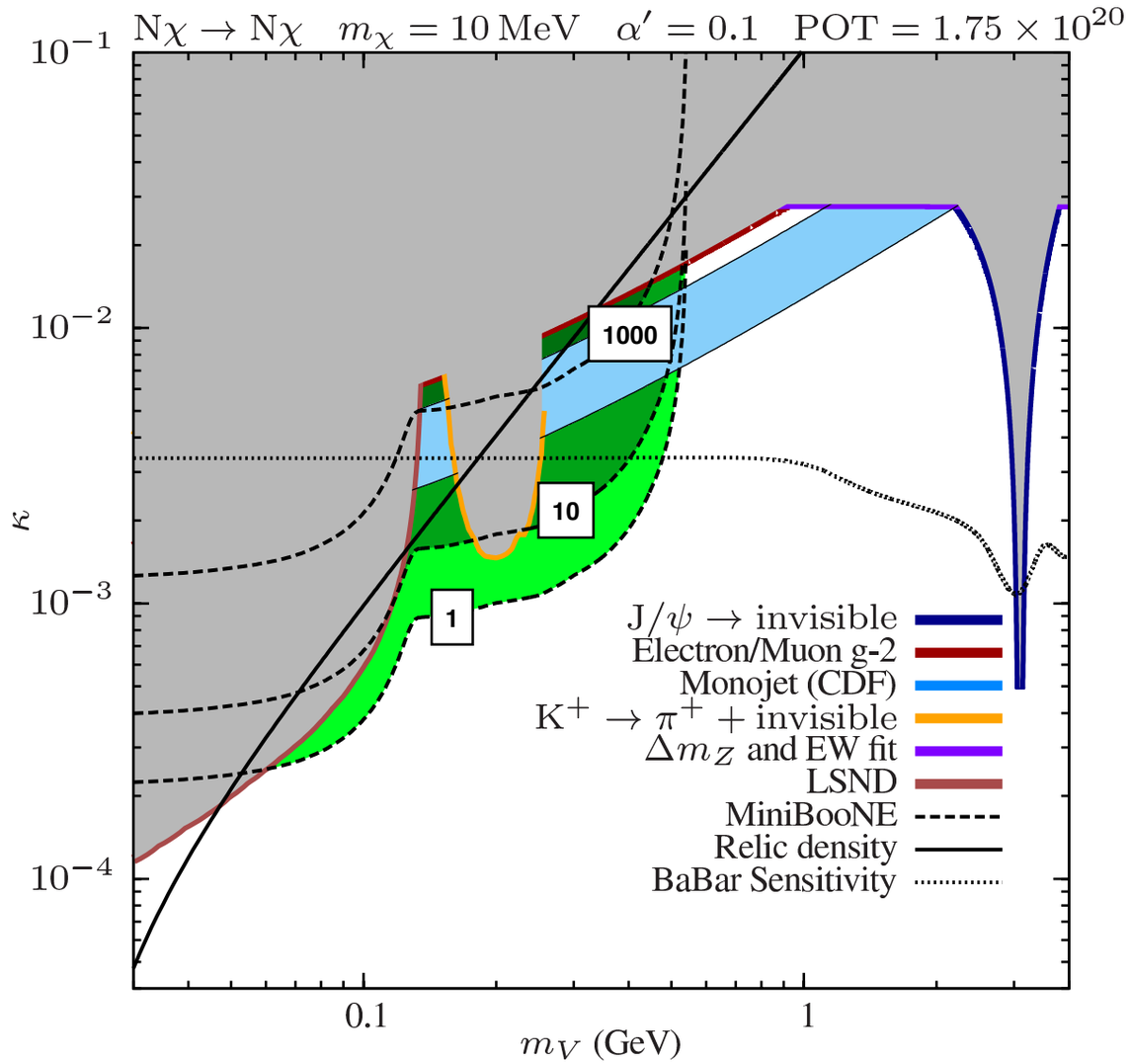
$\chi - e^-$ elastic

Dark matter signal Monte Carlo simulation:

- HARP/MiniBooNE Be target, Sanford-Wang meson production model
- MiniBooNE determined acceptance - PID, fiducial, and energy cuts
- Calculate regions of $m_\chi, m_V, \kappa, \alpha'$ parameter space with 1, 10, 1000 events

Dark Matter signal rates





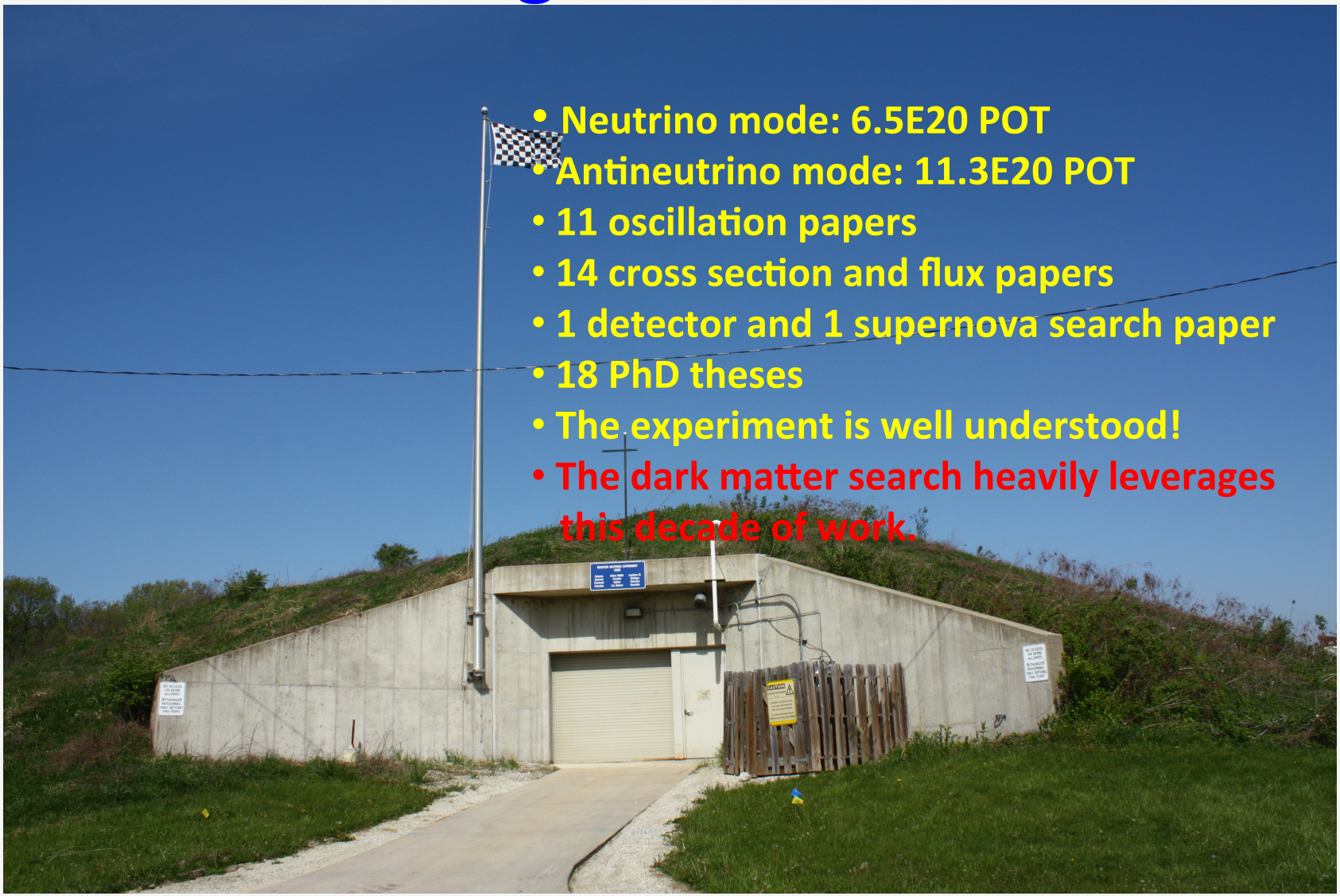
- MiniBooNE has best sensitivity in interesting parameter regions
- In other models (e.g., leptophobic), MiniBooNE has unique sensitivity!
- Complements "visible" searches for dark photon at JLAB, Mainz

The MiniBooNE Request

MiniBooNE requests running to collect a total of 1.5×10^{20} *POT in beam-dump mode. This will allow a sensitive measurement of the neutral current elastic nucleon event rate in a beam configuration mode that enhances any possible non-Standard Model contribution, with significant sensitivity to specific models of light dark matter in a parameter region consistent with the required cosmic relic density, and an explanation of the muon* $g-2$ *discrepancy. The experiment further requests that this beam be delivered in 2014 before the MicroBooNE experiment turns on.*

- Pioneering search for Dark Matter with a neutrino experiment
- Physics is compelling and explores uncharted territory
- Effort will produce publishable physics results
- Puts the idle Booster Neutrino Beamline (BNB) to good use in the period before MicroBooNE starts

Ten Years of Successful MiniBooNE Running and Results!



MiniBooNE Collaboration Committed to the Beam-Dump Run

A Proposal to Search for Dark Matter with MiniBooNE

Submitted to the FNAL PAC Dec 16, 2013

The MiniBooNE Collaboration

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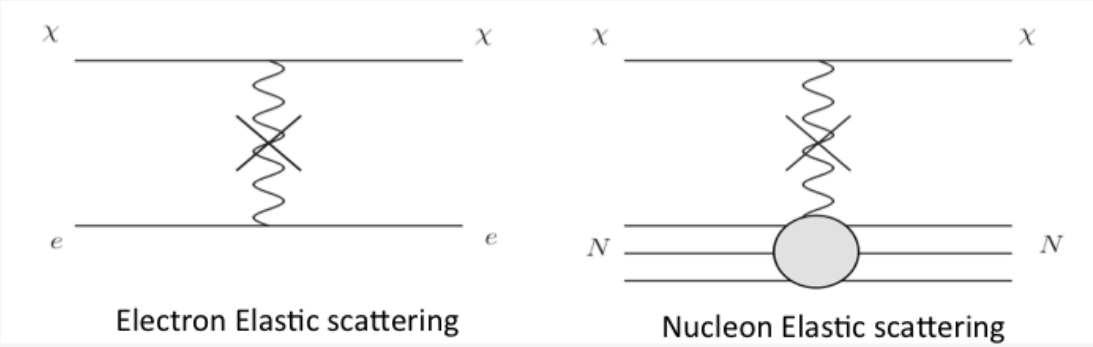
There has been growing interest in the MiniBooNE proposed dark matter search:

- Number of collaborators has increased from 28 to 44
- There is a strong theory contingent.
- Number of Institutions increases from 10 to 15, with one from Mexico, and one UK.
- There are more than enough collaborators to do shifts and analysis.

Work Since the Last PAC Request Nov 2012

- Further developed and refined the dark matter models and production using proton beams. Presented work at recent SNOWMASS and is written into the white paper
  - Ideas are now being investigated by MB+, MicroBooNE, LAr1-ND, LBNE near detector, and Project X
- Completed the dark matter-nucleon scattering analysis on the MiniBooNE neutrino and antineutrino data.
- Produced detailed event time of flight distributions, work on dark-matter time fits almost complete.
- Refined prediction in beam-dump mode with short test run this last fall.

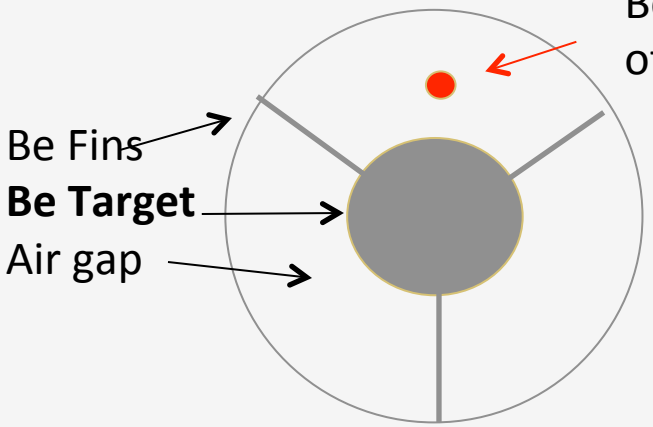
Enhancing the Dark Matter Search



- Dark Matter can interact in the oil scattering off nucleons and electrons:
  - Dark matter events look like neutrino Neutral Current (NC) scattering off nucleons or electrons but possibly with different kinematics (momentum, angle, timing, etc).
- Can use different techniques together or separately to extract signal:
  - Beam off target (beam-dump) running to significantly reduce the neutrino flux while leaving the signal unaffected.
  - Event energy and/or angle information.
  - Event time of flight relative to the beam.

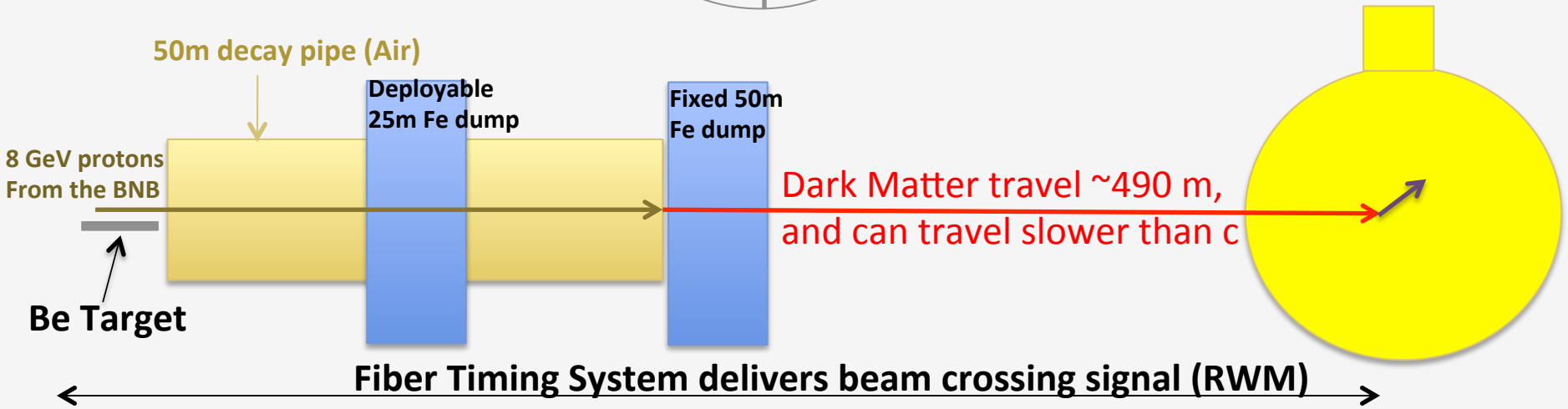
Beam Off Target Running (Beam-Dump Mode)

MB has the capability to steer the protons past the target and onto the 25m or 50m iron dump



Beam spot position in beam off target mode (~1 mm spread)

-Target is 1 cm diameter
-Air gap between target and horn inner conductor is ~1 cm



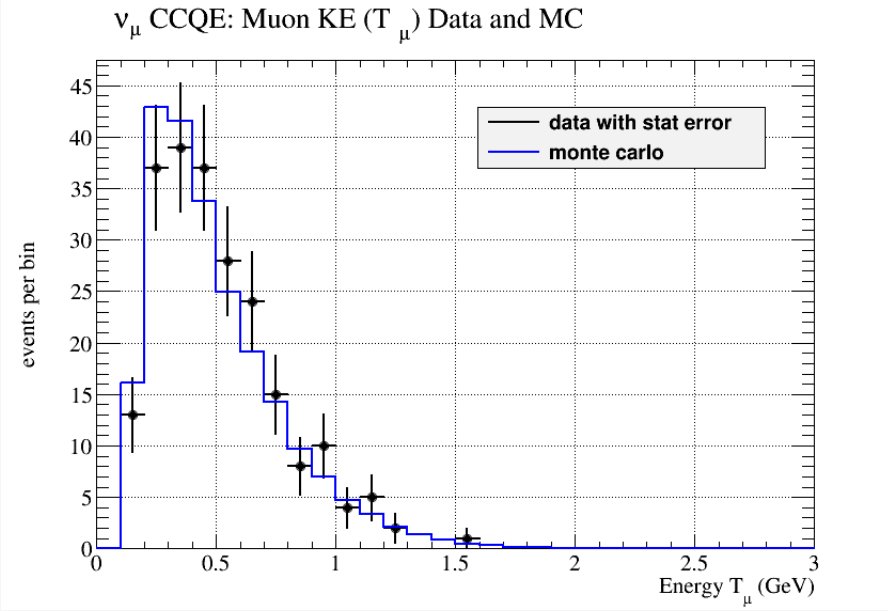
- π^0 and η produced by protons in the Fe quickly decay producing dark matter.
- Charged mesons are absorbed in the Fe before decaying, which significantly reduces the neutrino flux (still some production from proton-Air interactions).

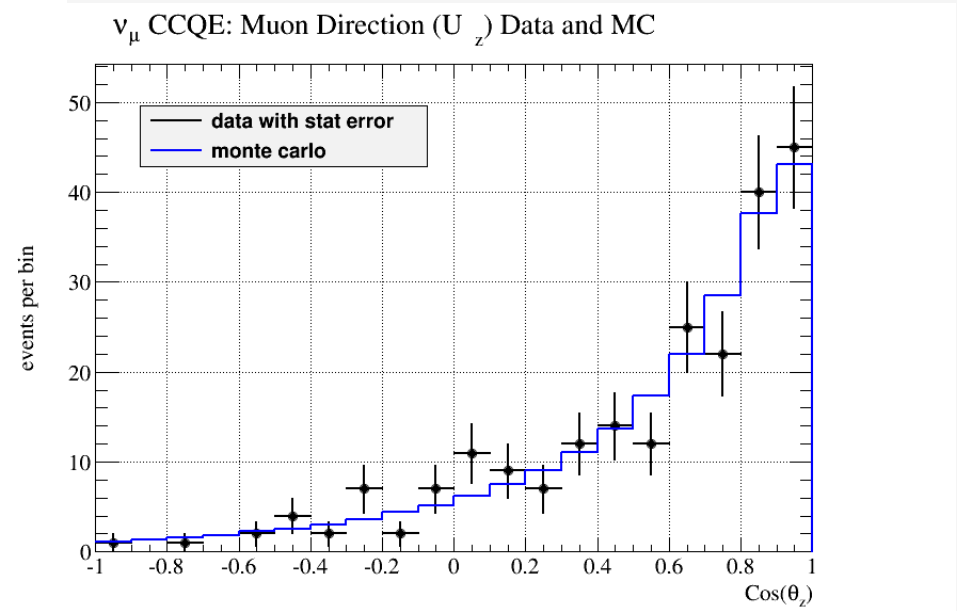
Fall 2013 Beam-Dump Test Run

- Performed short test run to collect 3.5×10^{19} POT in beam-dump mode to:
  - Re-commission the Booster Neutrino Beamline (BNB) after a 1.5 year shutdown and make ready for MicroBooNE.
  - Provide a high power beam-dump for high intensity running (tuning) of the Linac/Booster.
  - Test new BNB hardware: Dual low mass multiwires and fiber RWM timing, which will also be used by MicroBoonE.
  - Collect enough data to check beam-dump rate reduction and background rates, which is an important input to determining robust sensitivities.
  - Projected POT to end of May now 1.5×10^{20} POT.

Neutrino Rate Reduction in Beam-Dump Mode

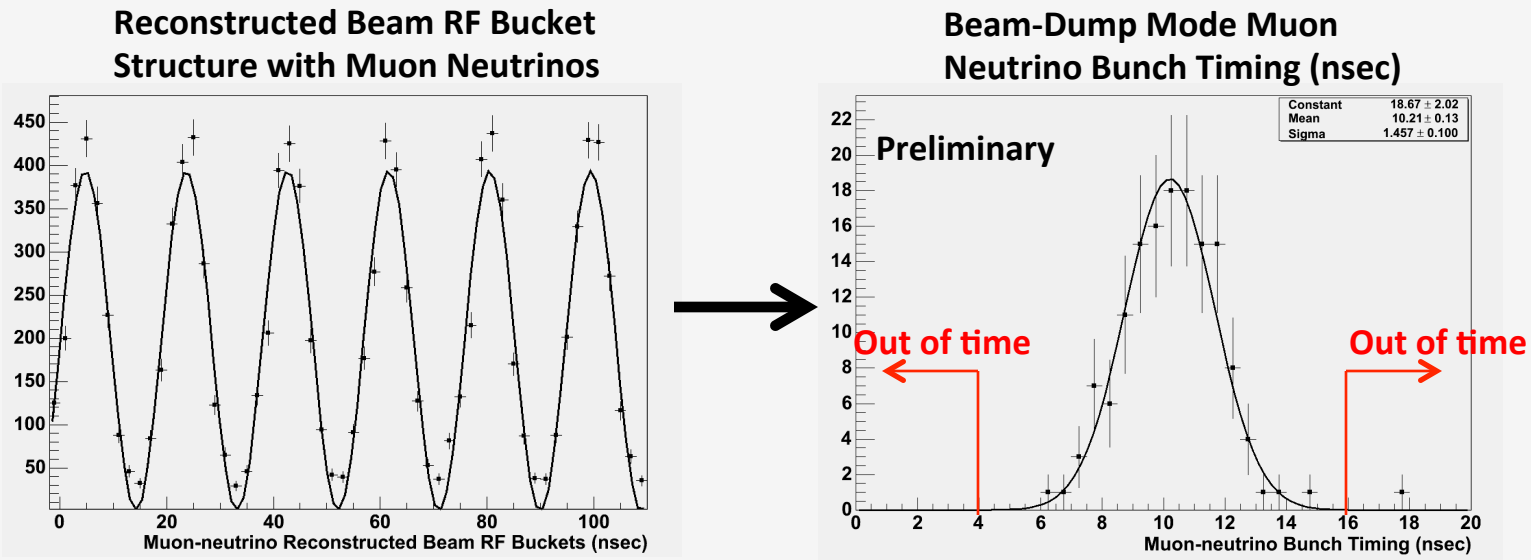
- Estimated neutrino rate reduction:
  - **DATA**: 50m absorber test beam off target run (3.19×10^{19} POT):
    $(\text{events/POT})^{\nu \text{ mode}}/(\text{events/POT})^{\text{beam off target}}$ = **44 ± 3 (stat error)**
- We will normalize the MC rate to the observed muon CCQE rate, and assume kinematics are the same This was the same procedure for the oscillation analysis.



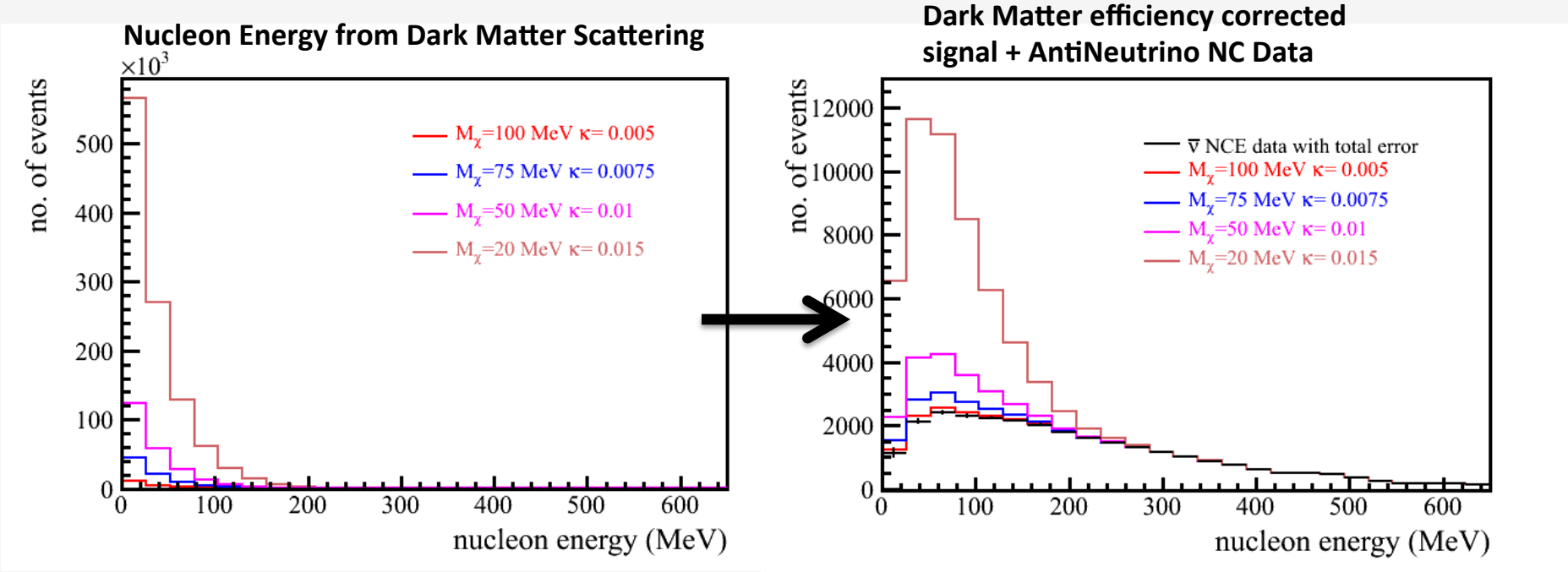


Improved RWM Beam Timing for Time of Flight Measurements

- New fast timing discriminator and fiber system delivers beam crossing signal to the detector more reliably.
- Muon neutrino timing improved from 1.8 nsec to 1.5 nsec, which will enhance the time of flight measurement.
- Neutral Current Scattering timing will be worse due to event reconstruction based on scintillation light (~4.2 nsec).



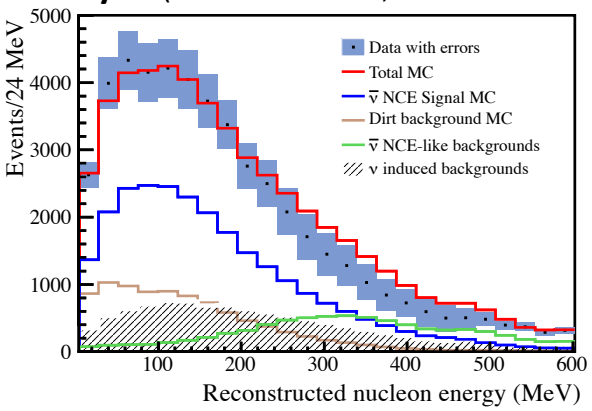
Dark Matter-Nucleon Scattering Energy



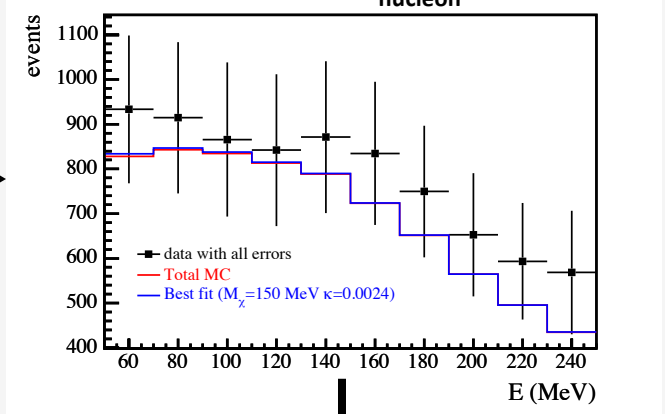
- For different model parameters, the dark matter signal is below 250 MeV nucleon energy.
- Signal falls off rapidly below 40 MeV due to detector reconstruction efficiency.
- Fit the dark matter template plus the neutrino background prediction to the data. Use full NC cross section error matrix.

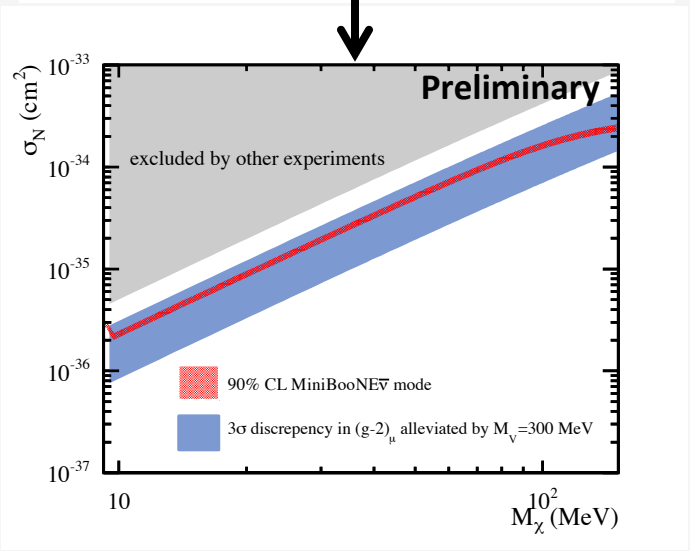
Dark Matter-Nucleon Scattering in Antineutrino Mode

Antineutrino NCE data cross section analysis (arXiv:1309.7257, submitted to PRD)



Dark Matter Scattering Fit from 50 MeV < $E_{nucleon}$ < 250 MeV



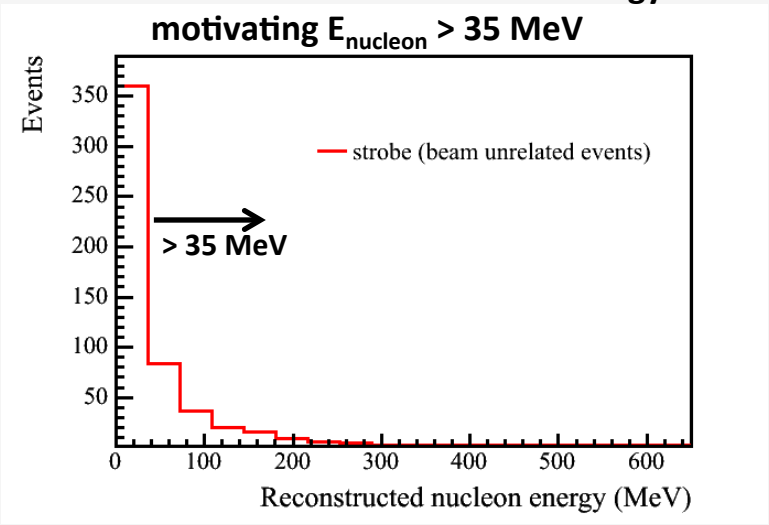


- Dark Matter- Nucleon scattering limits from the antineutrino data suffer from large neutrino induced backgrounds.
- Neutrino mode x4 worse.
- Timing helps.
- **We need beam-dump mode!**

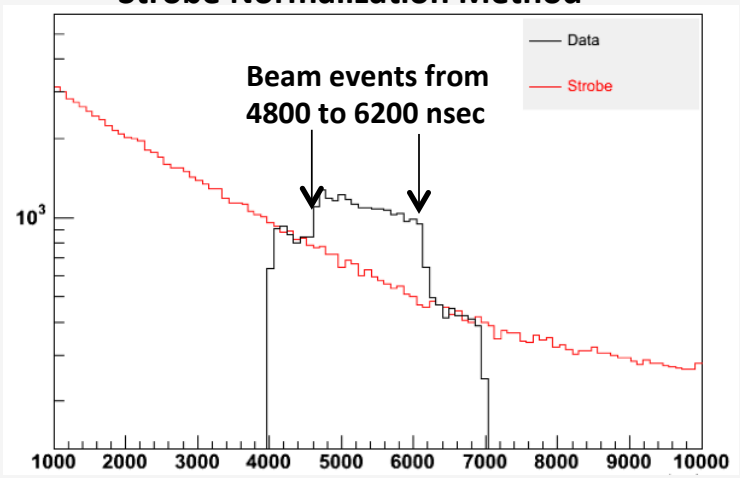
Beam-Unrelated Background Dominate in Beam-Dump Mode

- Beam-unrelated background dominated by cosmic rays, especially at low energy. Motivates $E_{nucleon}$ > 35 MeV cut.
- Measure beam-unrelated events with a 15 Hz continuous strobe trigger that uses the same DAQ window as for beam.
- Two methods of data normalization agree. Systematic errors on beam-unrelated background 2%.
- Working on method to reduce beam-unrelated rates by a factor of two.

Strobe measured nucleon energy motivating $E_{nucleon}$ > 35 MeV

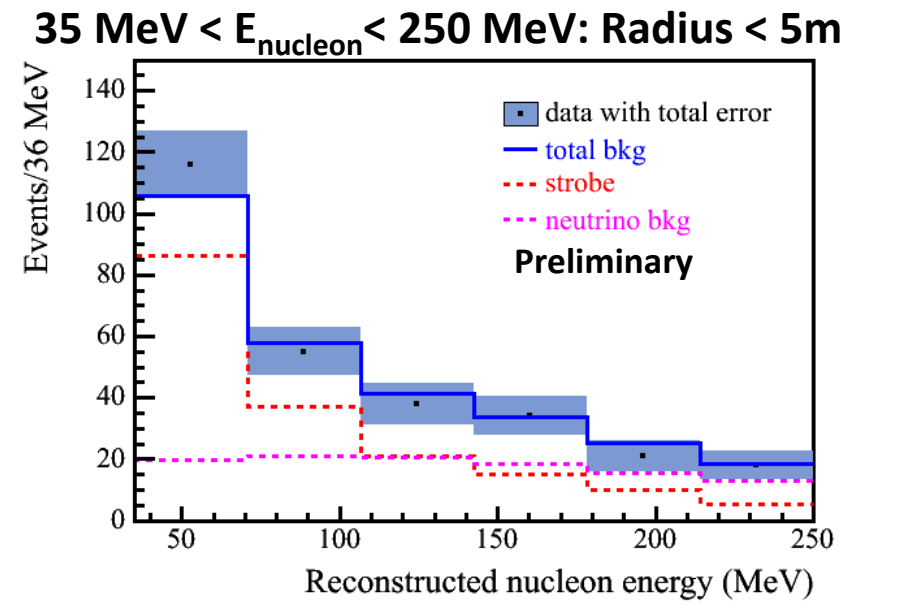


Strobe Normalization Method



Dark Matter-Nucleon Scattering with 3.19×10^{19} POT Beam-Dump Mode

- Similar event reconstruction as in antineutrino analysis. Monte Carlo neutrino background prediction tied to measured muon CCQE rate.
- Background stat error dominated by Beam-unrelated (strobe) events.
- Data in agreement with background predictions. Currently ~16% systematic error on NC neutrino background.

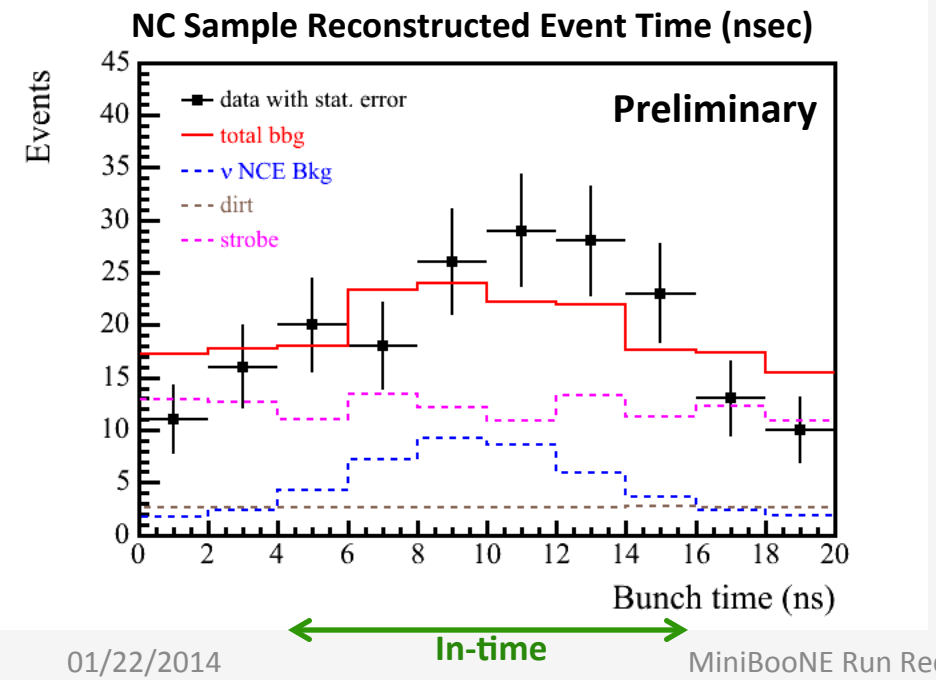


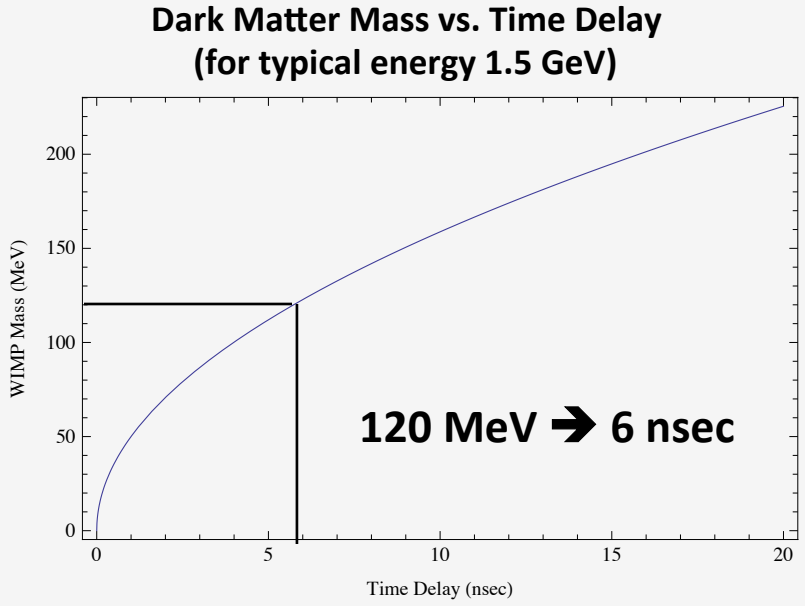
	#events	
strobe	177	
nu bkg	107.8	
Total Bkg	284.8	+/-18 (systematic)
data	282	+/-17 (statistical)

Total error= 24.6 events, or 23% of nu bkg

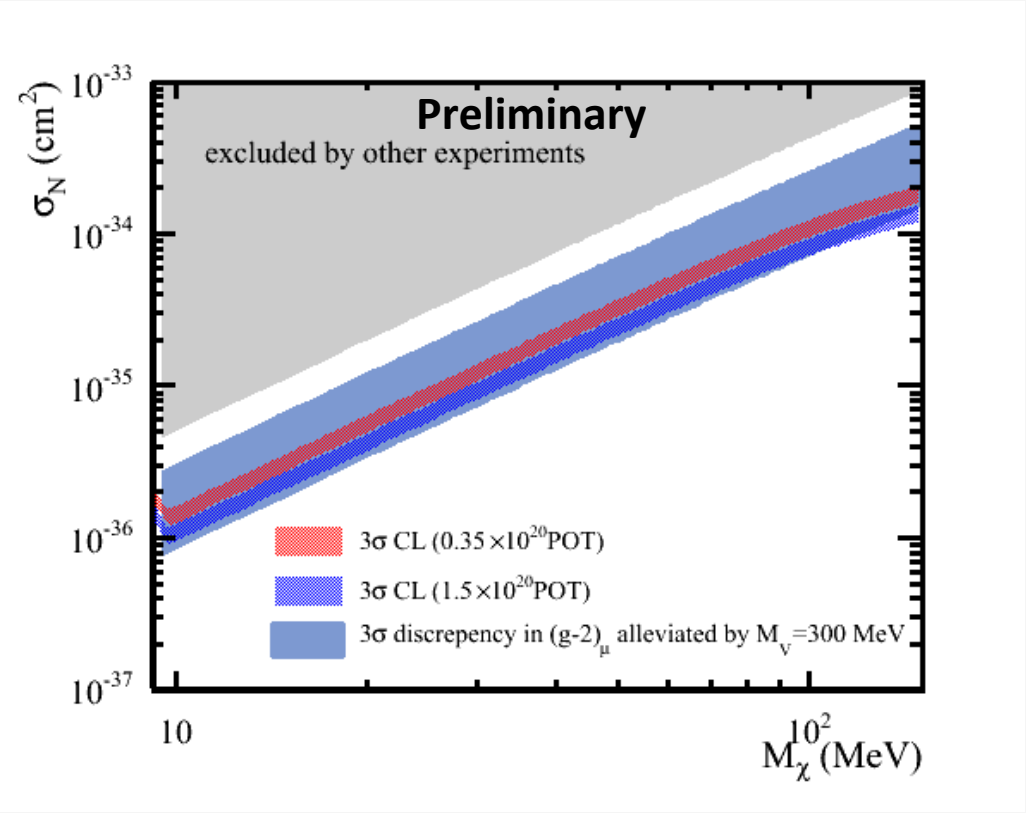
Neutral Current Data Timing for 3.19x10^{19} POT Beam-Dump Mode

- Neutrino NCE events have 4.2 nsec timing resolution.
- Beam-unrelated and neutrino dirt interactions are flat in time.
- **In-time (4-16 nsec) region** rejects flat backgrounds, enhances M_{DM} < 120 MeV.
- **Out-time (0-4; 16-20 nsec) region** rejects NCE bkgs, enhances M_{DM} > 120 MeV
- More sophisticated dark matter time distribution fits being developed.





3σ C.L. Sensitivities for Dark Matter-Nucleon Scattering in 50m Beam-Dump Mode



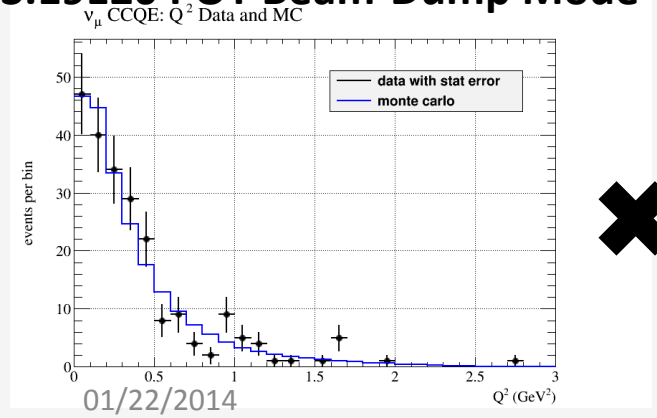
Width of band represents signal production systematics

- Cover g-2 region with 1.5×10^{20} POT (In-time analysis) for α' = 0.1
- 0.35×10^{20} POT test run has verified background estimates.
- In the center of the g-2 band expect ~600 dark matter events for 1.5×10^{20} POT, or > 8σ signal significance

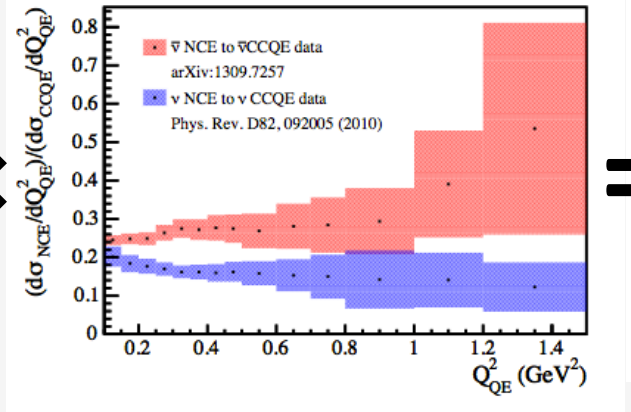
Improvements Using the Measured NC/CCQE Cross Section Constraint

- We are developing a method to predict the beam-dump mode neutral current (NC) nucleon rate with the measured CCQE muon rate weighted by the NC/CCQE cross section ratios from both neutrino and antineutrino mode.
- With increased statistics in beam-dump muon CCQE channel, the systematic errors of the method will decrease.
- This will result in 9% NC systematic error for 1.5E20 POT (12% for 0.35E20POT). Statistical errors will be equivalent.

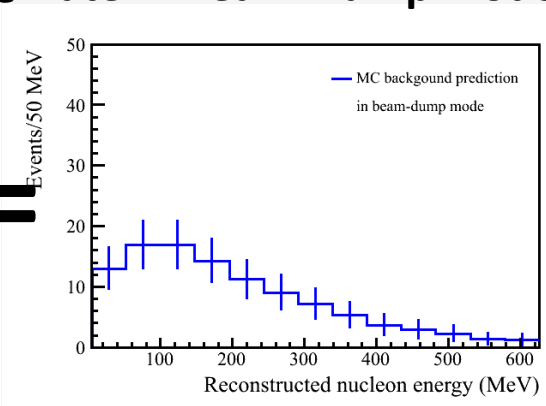
Measured CCQE Muon Rate 3.19E20 POT Beam-Dump Mode



Measured NC/CCQE cross section in nu and antinu mode

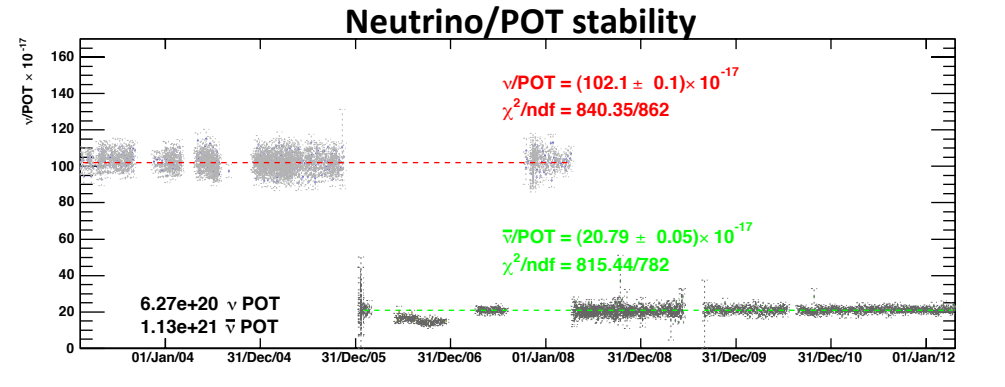


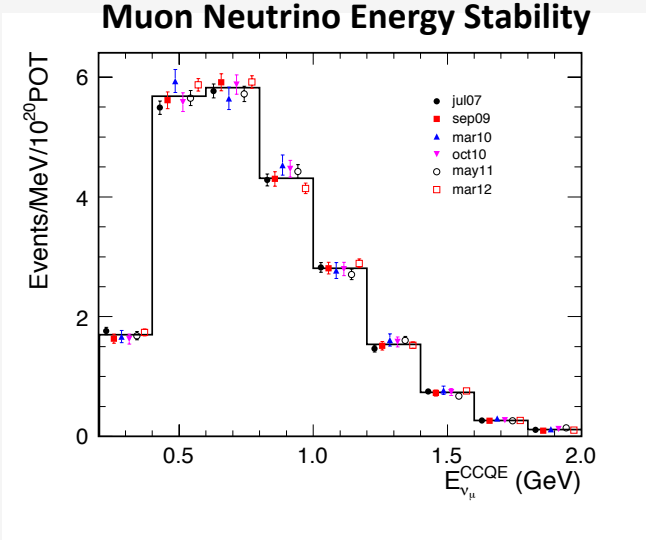
Constrained NC background rate in Beam-Dump mode



Run Stability and Logistics

- **MB running has been stable for 10 years:**





- Can continue stable running for the next six months. Will keep the beamline tuned up for MicroBooNE.
- The infrastructure costs of further running are relatively small. Cost to run BNB essentially the same since Accelerator Division will keep the beamline up and running low intensity to prepare for MicroBooNE.
- There are enough collaborators (42) to run shifts. Remote shifts also reduces the shift duty burden.
- There are enough analysis experts on hand to perform the analysis. If approved a few PhD students could be recruited to work on proposed physics.

Future Experiments to Search for Dark Matter with FNAL Accelerators

- Developing dark matter-electron scattering analysis (see backup slides)
- Run BNB with 25m absorber to perform systematic check of any observed signal (see backup slides).
- MB+ and MicroBooNE are investigating sensitivity with Beam-Dump run.
  - MB+ scintillator has boosted nucleon identification.
  - MicroBooNE has excellent signal efficiency and background rejection.
- Both LAr1-ND and LBNE near detectors will have sensitivity.
  - LAr1-ND is only 50m from BNB dump. High signal event rate.
  - LBNE has advantage of 120 GeV protons with extends the dark matter mass reach up to a few GeV.
- Project X can provide increased protons to any of these proposals.
- A workshop this spring at FNAL will discuss and further investigate these ideas.

Summary

- The run being proposed is a demonstration of the feasibility and sensitivity of low mass dark matter searches at accelerators using proton beam dumps.
  - We are asking for a short ~6 month run to collect a total of 1.5×10^{20} POT in beam-dump mode.
  - This type of proton dump search is unprecedented in terms of number of POT, large detector size, and sensitivity to anomalous NC interactions.
- This run will result in at least 1-2 papers that will produce relevant dark matter limits.
  - MiniBooNE will explore new regions of low mass dark matter parameter space that are consistent with relic density estimates and a possible explanation for the muon g-2 anomaly.
  - Our theory team is looking into other production and interaction modes.
- Through the SNOWMASS process, this novel search has been introduced to the intensity frontier community and found to be worthwhile with other neutrino experiments considering searches themselves.
- **If successful, this could motivate future proposals for dedicated beam dump experiments using existing FNAL accelerators, or with Project X.**

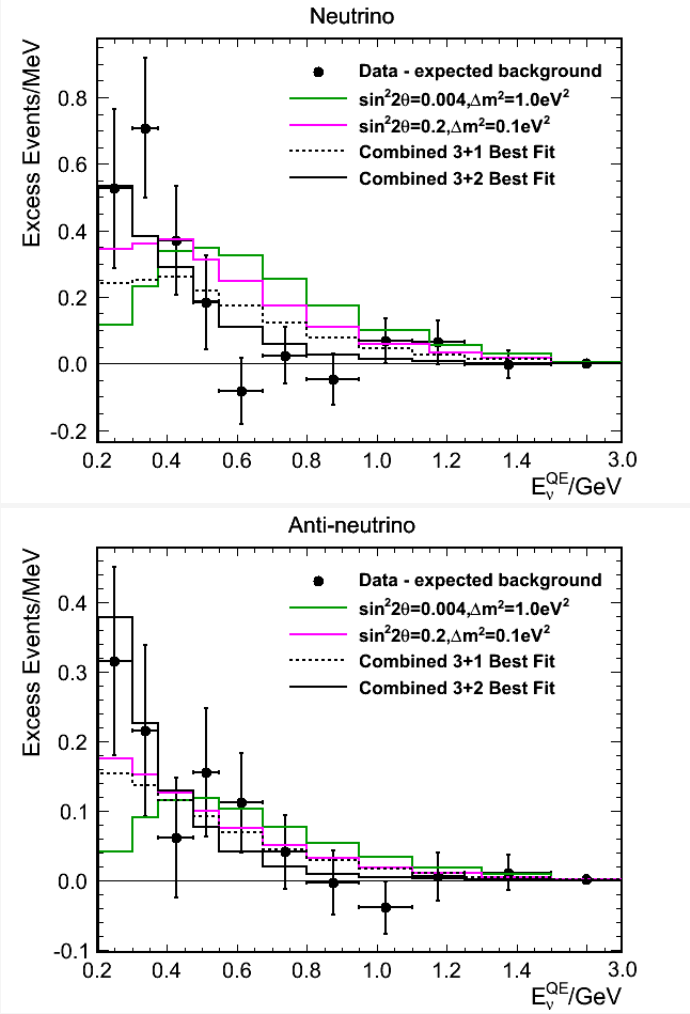
The MiniBooNE Request

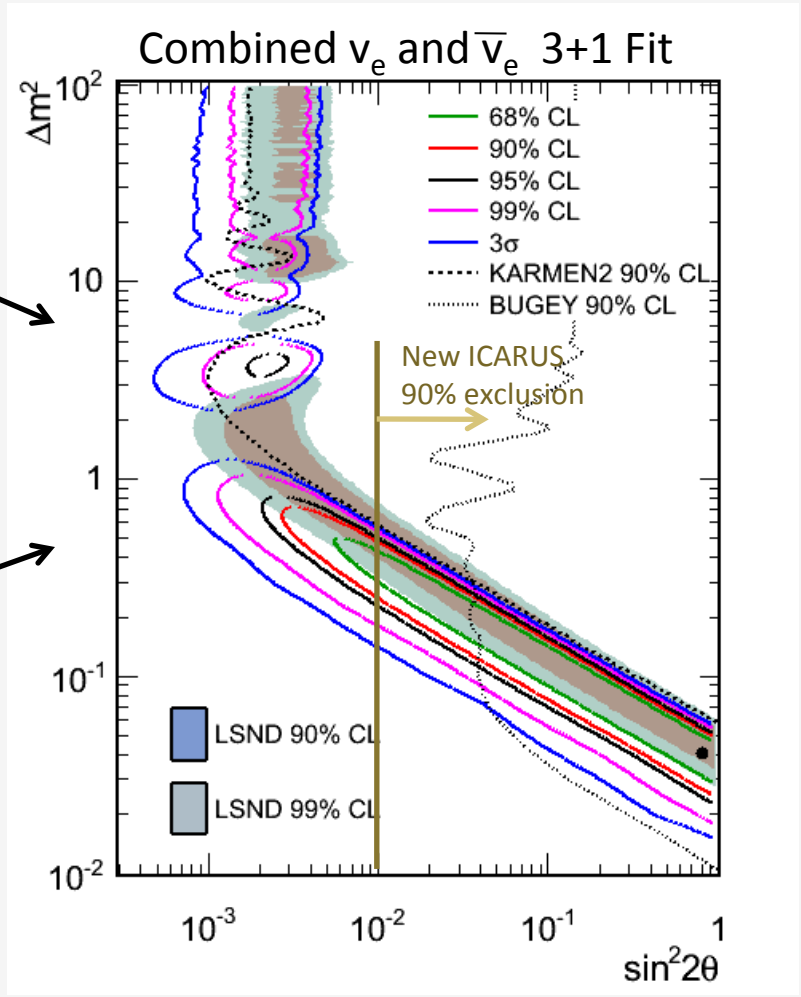
MiniBooNE requests running to collect a total of 1.5×10^{20} *POT in beam-dump mode. This will allow a sensitive measurement of the neutral current elastic nucleon event rate in a beam configuration mode that enhances any possible non-Standard Model contribution, with significant sensitivity to specific models of light dark matter in a parameter region consistent with the required cosmic relic density, and an explanation of the muon* $g-2$ *discrepancy. The experiment further requests that this beam be delivered in 2014 before the MicroBooNE experiment turns on.*

- We have already made the investment in the detector and the beamline, let's capitalize on that investment to explore this unique physics opportunity relevant to the dark matter sector and possibly muon g-2.

BackUp Slides

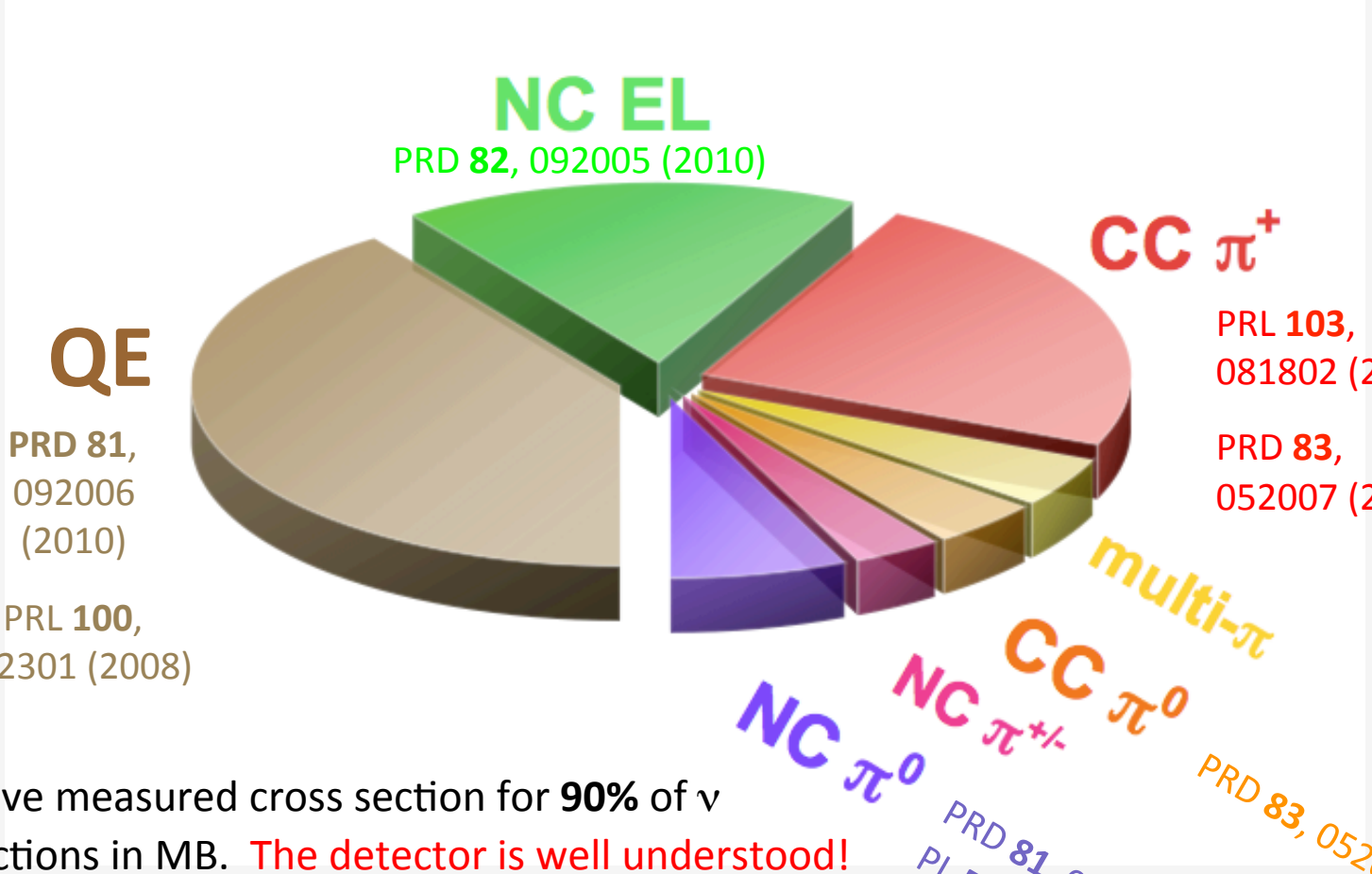
Ten Years of MiniBooNE Running: Oscillation Results





- Combined ν_e and $\underline{\nu}_e$ Event Excess from 200-1250 MeV = 240.3+-34.5+-52.6 (3.8σ)

Ten Years of MiniBooNE Running: Cross Section Results



- We have measured cross section for **90%** of ν interactions in MB. The detector is well understood!
- Additional $\overline{\nu}$ results to be reported this fall.
- These results have motivate much new and needed theoretical work on neutrino nucleus scattering.

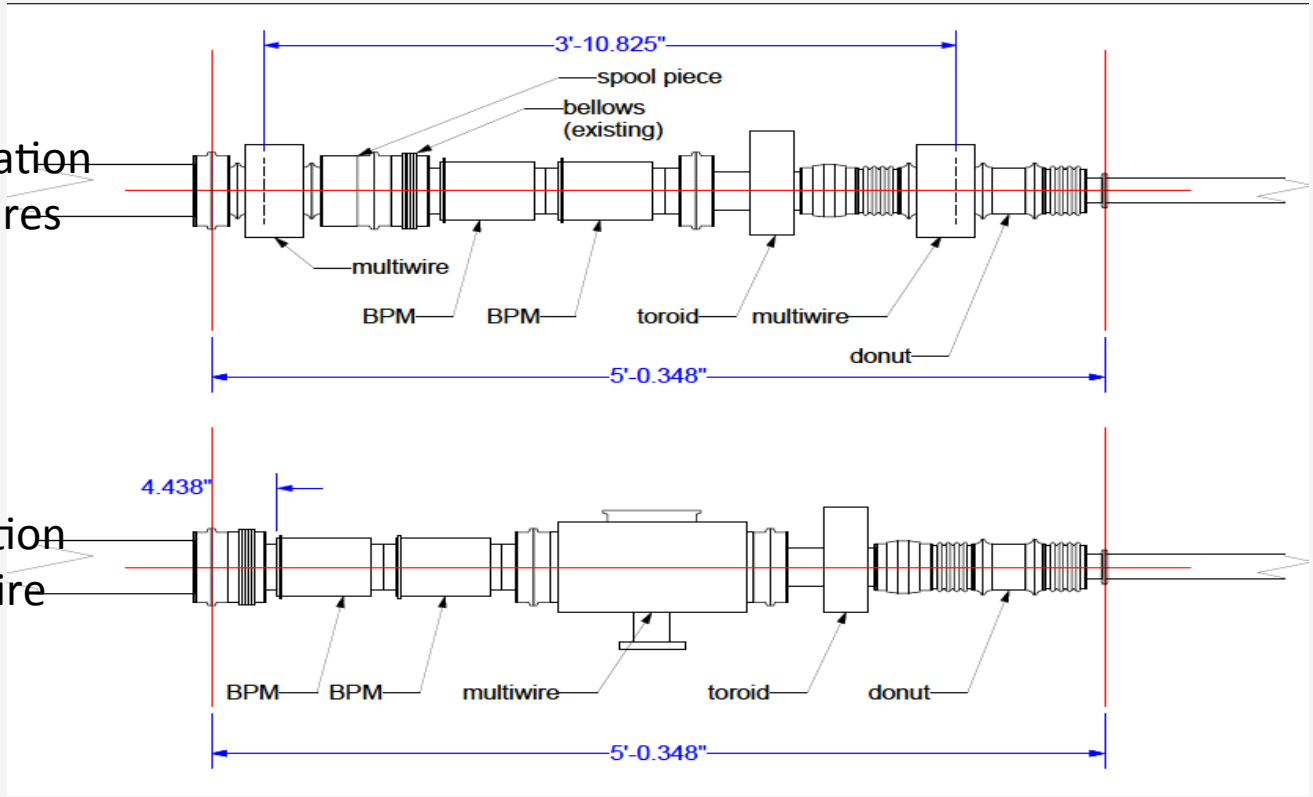
Is Further Neutrino/AntiNeutrino Running with no Changes Worthwhile?

- Neutrino Running: NO -- we are systematic limited, more running would not significantly improve the results.
- Antineutrino Running: Maybe – we are still statistics limited, but would take many years to double the data.
- We need a significant systematic change to add new information to the question of oscillations.
  - Submitted a proposal to add scintillator to the detector and run concurrently with MicroBooNE – next talk by Rex Tayloe

Upgrades to Beam Positioning

NEW configuration with 2 multiwires

Old configuration with 1 multiwire

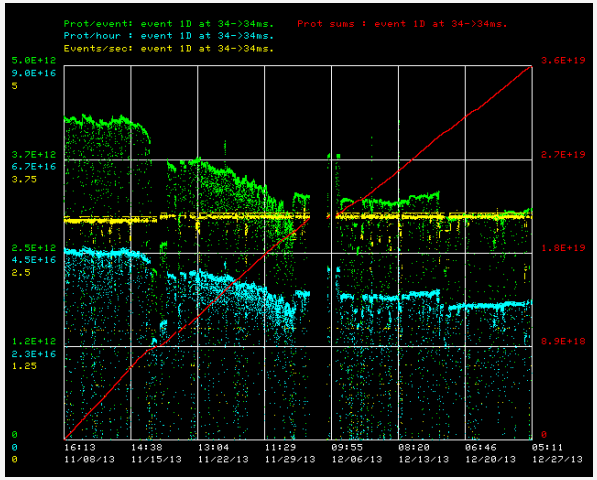


- With new dual low mass multiwires, will be able to reliably point the proton beam at the detector to within 0.5 mrad, or about 25 cm spatial resolution. **Will allow for searches of beam directed exotic physics (beam-strahlung) such as axions, paraphotons, etc.**

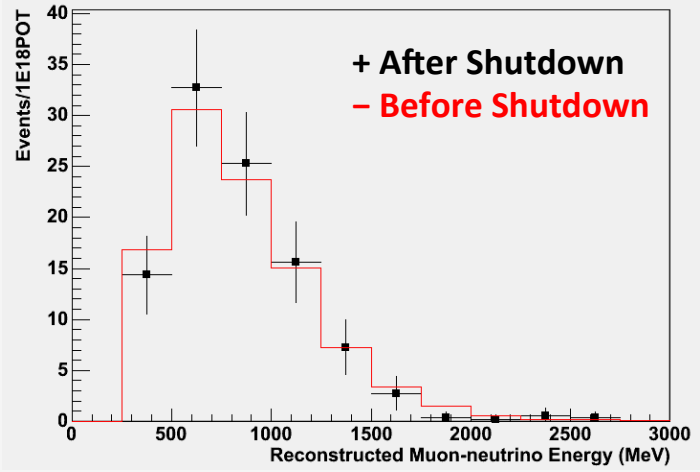
Test Run Checks

- Reliable BNB and detector running at ~5E18 POT/week.
- Projected to end of May 2014, will collect ~1.5E20 POT.
  - We are only taking beam that is available, which might decease in the future.
- One week antineutrino mode (beam-on-target and horn-on) run demonstrates that beamline elements (target, horn, decay pipe) are working normally.

Beam Performance

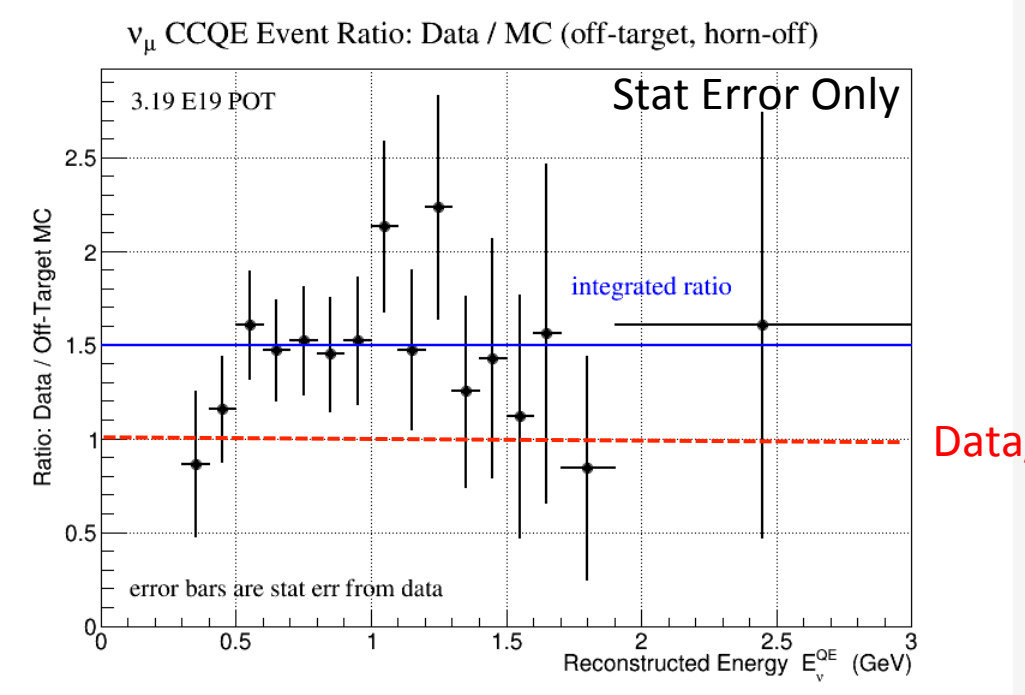


Antineutrino Rate and Energy Consistent



Measured Neutrino Rate Reduction with Beam-Dump Test Run

- Estimated neutrino rate reduction:
  - **DATA**: 50m absorber test beam off target run (3.19x10^{19} POT):
    (events/POT)$^{\nu\ mode}$/(events/POT)$^{beam\ off\ target}$ = **44 ± 3 (stat error)**
- Systematic errors about 15%. Working to understand Data/MC disagreement.

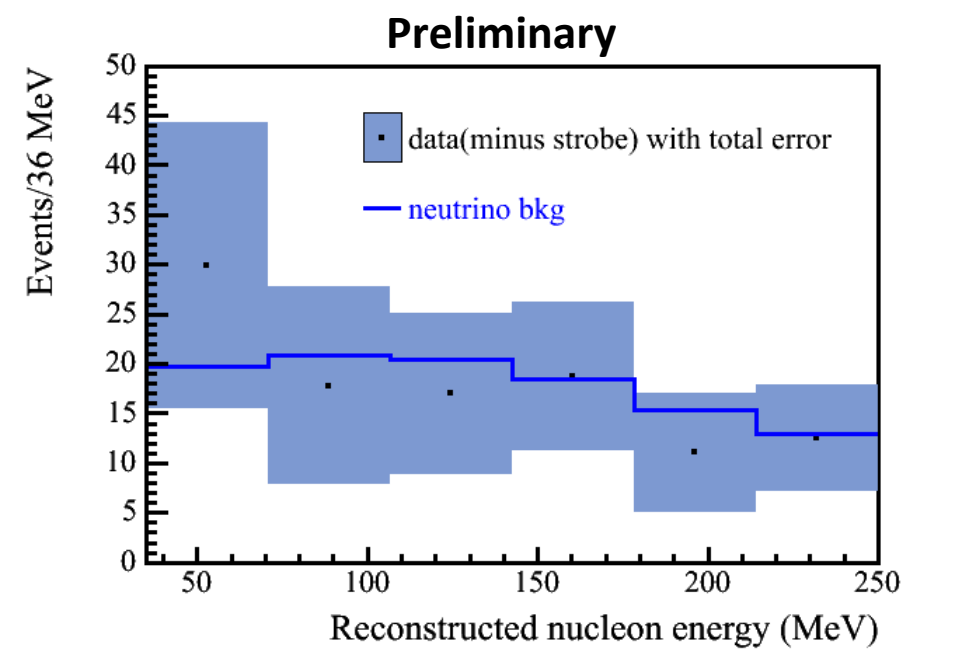


228 CCQE muon neutrinos reconstructed with 3.19x10^{19} POT

Data/MC= 1

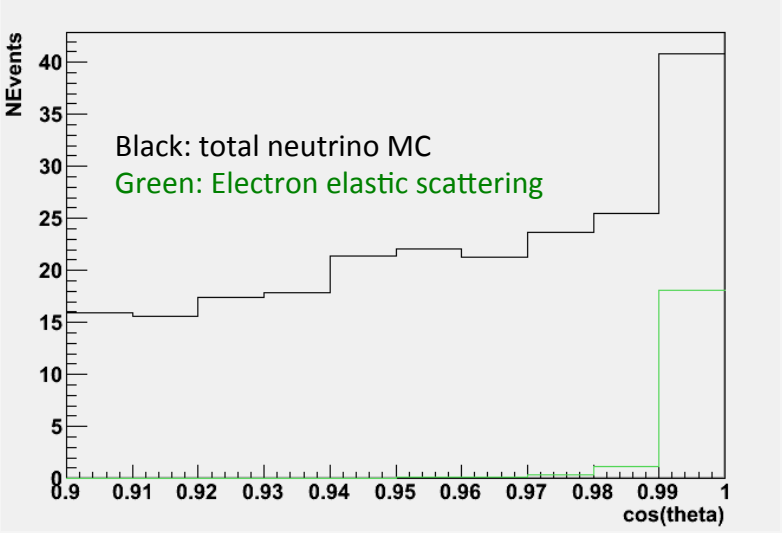
Dark Matter-Nucleon Scattering with 3.19×10^{19} POT Beam-Dump Data

- NC neutrino induced background after beam-unrelated correction, which has large statistical error.
- Total errors 23%, equal statistical and systematic error.
- Dark matter fits performed to this distribution.

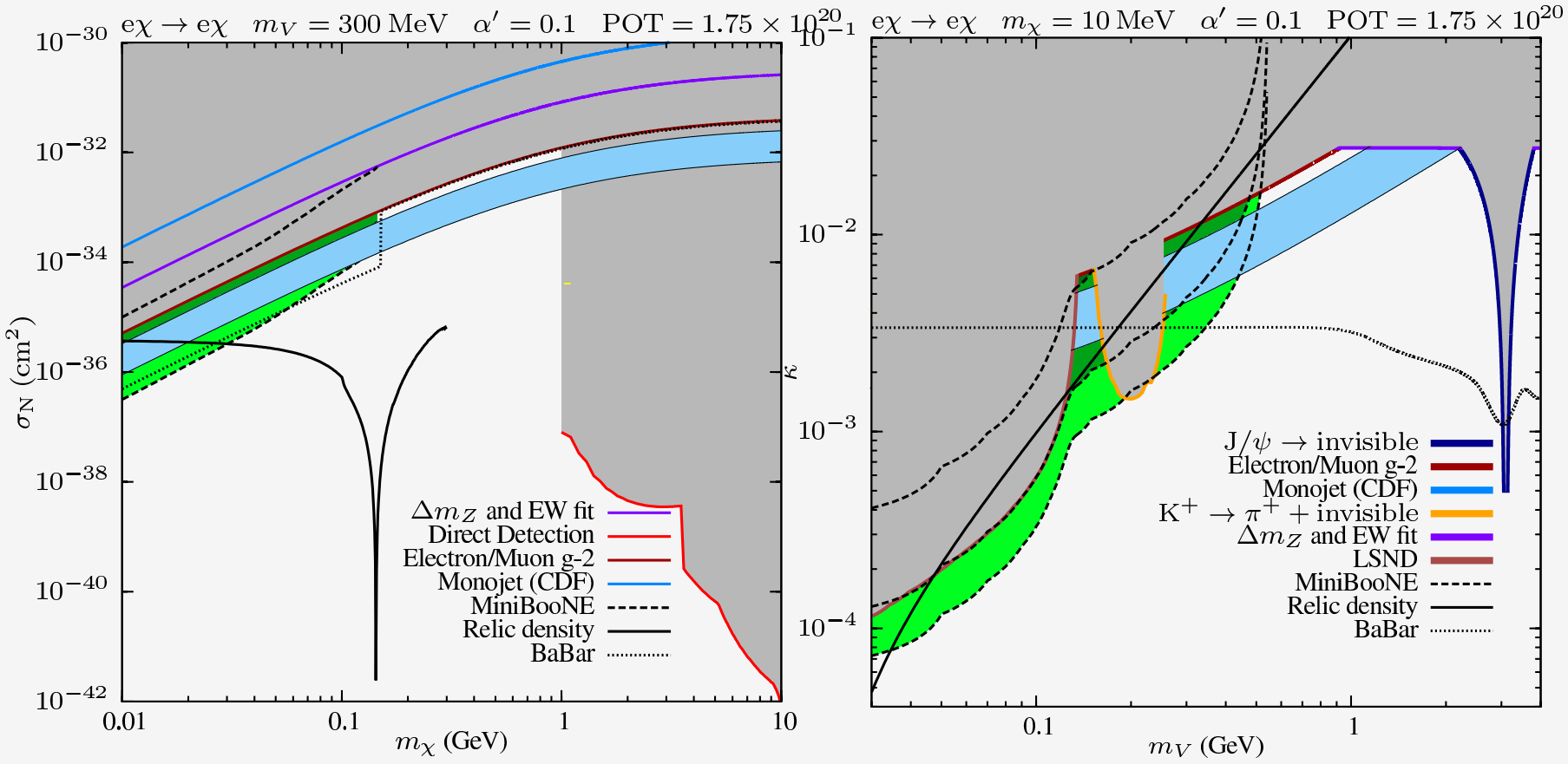


Dark Matter-Electron Scattering

- Dark matter-electron scattering is forward peak. With a forward angle cut, can reject 98% of neutrino induced backgrounds.
- Systematic errors around 12%.
- Requires dropping the current energy threshold of > 140 MeV. Much of the dark matter-electron scattering signal resides below this.
- A team is currently pursuing this analysis.



90% C.L. Sensitivities for Dark Matter-Electron Scattering: 1.75E20 POT Beam-Dump Run



- Electron channel will have smaller backgrounds, and can cover a significant part of the muon g-2 signal region.

Signal Systematic Check with 25m Absorber Running

- It will take >5E20POT of 50m absorber running to cover the entire g-2 region at 5σ.
- Most neutrinos produced by p-Air interactions in the decay pipe. Deploying 25m absorber reduces neutrino backgrounds by a factor of two.
- Achieve good sensitivity with 25m with only 1E20POT.